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DEFORMATION MONITORING OF FLOOD PREVENTION DAMS USING GEODETIC AND FIBRE OPTIC MEASUREMENT TECHNIQUES

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ABSTRACT

Flood prevention dams with high stability are necessary for reliable protection from catastrophic events. A series of life-size experiments was carried out to investigate innovative slope stabilization methods for such dams. In these experiments, vertical load was gradually increased. The Institute of Engineering Geodesy and Measurement System designed a structural monitoring system to investigate the relationship between applied loads and resulting deformations. The developed monitoring system is based on geodetic and fibre optic measurements. Robotic total stations were used to simultaneously track targets on the slope and to determine deformations in real-time. Additionally, the whole slope surface was periodically monitored by a scanning total station. It is found that deformations of the whole dam surface can be reliably derived from the collected point clouds.

However, individual loading steps cannot be resolved due to the limited precision of the dynamic geodetic measurements which is about 1mm. The sensitivity of the monitoring system was significantly increased by connecting points on the slope with fibre optic sensors based on fibre bragg gratings (FBG). Our results demonstrate that the FBG sensors can depict each individual loading step. The fibre optic sensors complement the geodetic deformation measurements and enable detailed investigations on small-scale deformations which are critical for early warning within a structural health monitoring system.

KEYWORDS

Structural health monitoring, deformation analysis, fibre Bragg grating, scanning total station, flood prevention dam.

INTRODUCTION

In 2012 a new hydroelectric power plant was built on the river Mur in the south of Graz, Austria (Figure 1). Earth filled flood protection dams were erected on both sides of the river as part of the safety plan of this project (Semprich *et al*. 2012).

Figure 1. Water power plant Goessendorf with flood prevention dam

An experimental dam with the dimensions 3.5m (width) x 3.0m (height) x 27.0m (length) was constructed in the vicinity of the water plant to verify the stability of the flood prevention dams, see Figure 2. The dam material of the test dam was the same as the material used for the flood prevention dams. In the experiments slope failures in longitudinal direction were forced by applying vertical loads up to 800kN/m² on the dam crest in steps of $50kN/m^2$ and $100kN/m^2$ respectively. The duration of one test was approximately 2h. The goals of these experiments were the determination of the shear parameters of the dam material, the evaluation of the performance of modern slope stabilization methods and the assessment of different monitoring methods. In this paper, we focus on the development of the monitoring program and the evaluation of the sensors used.

Figure 2. Experimental dam in the vicinity of the hydroelectric power plant

EXPERIMENT SETUP

In total seven experiments have been carried out. In each experiment vertical load was applied onto the dam crest with a steel traverse and two hydraulic presses. The dam was either not stabilized (Figure 3-left), stabilized with two Spideranchors (Figure 3-centre) or stabilized with two Spideranchors and a geotextile (Figure 3-right). A Spideranchor consists of an iron anchor head and iron rods which are screwed through this anchor head in different angles into the ground (Supp and Semprich 2012).

The reaction of the dam surface to the applied load had to be measured in order to assess the stability of the dam. Furthermore, the movements of the anchor points were of special interest.

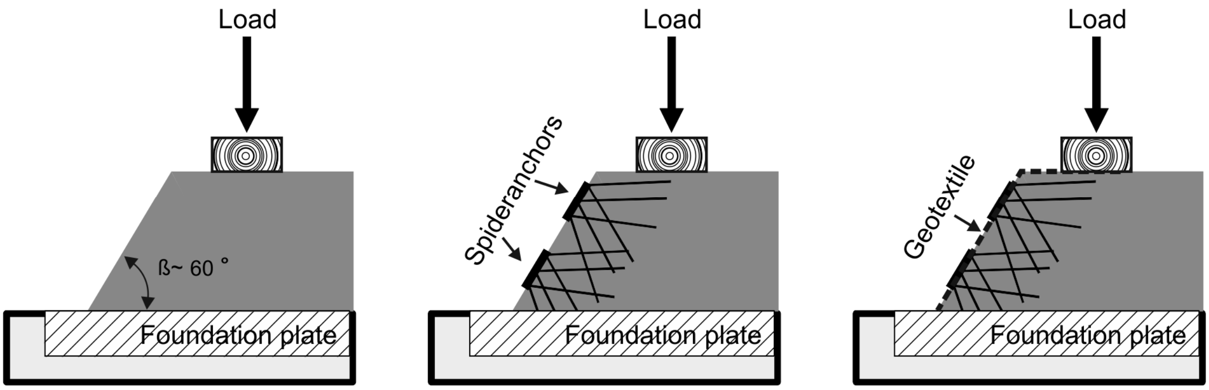


Figure 3. Different experimental setups: no stabilisation (left), stabilisation with Spideranchors (centre) and stabilisation with Spideranchors and geotextile (right)

MONITORING SYSTEM

The Institute of Engineering Geodesy and Measurements System (EGMS) of Graz University of Technology designed the monitoring system for these experiments. The monitoring system consists of a geodetic and a fibre optic component which complement each other due to their different precision and information content.

Geodetic Monitoring Concept

It was expected, that the dam suddenly fails under load. Thus, continuous 3D measurements with a high precision and a high sampling rate were necessary. Using two total stations it was possible to monitor two points on the slope equipped with geodetic prisms with a precision of about 1mm and a sampling rate of about 8Hz. Therefore, prisms were mounted with a special adapter on the anchor head of each Spideranchor. Figure 4-left shows a close up view of one anchor head. In order to measure inclination changes of the Spideranchors, inclinometers were also mounted on the anchor heads. Figure 4-right displays the overall setup. The prism P1 was tracked by total station T1 (Leica Geosystems TS15) and the prism P2 by total station T2 (Leica Geosystems TPS1200). A third point P3 was installed as reference point on the ground plate of the dam and sporadically controlled for stability. The positions of the total stations were determined by free stationing at the beginning of the experiments using a local reference point network and controlled again at the end of the experiment. Meteorological data for the atmospheric correction of the distance measurements was also collected. Both total stations were remotely controlled. The steering software as well as the data analysis software were developed by EGMS.

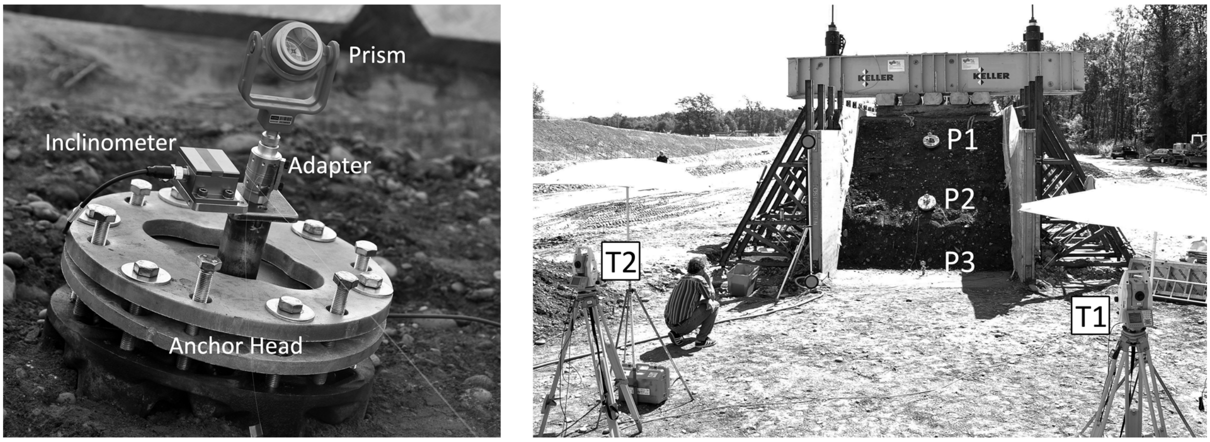


Figure 4. Measurement setup for the continuous monitoring of the anchors heads: detail view of monitoring point (left), overview with total stations (right)

The whole dam surface was scanned with the new scanning total station Leica Geosystems MultiStation MS50. This instrument has full total station functionality, fast direct drives and can measure up to 1000 points per second (Leica Geosystems 2013). For this application it was better suited than a laser scanner because no special reference targets and no post-processing in the office are needed. The surface scan was repeated at the end of each loading step. Furthermore, the MS50 was also used to assess the tracking performance of the two total stations T1 and T2. At specific time intervals the scanning operation of the MS50 was stopped and the instrument was used to measure the positions of the prisms P1, P2 and P3 in a more precise static measurement mode. These accurate single point measurements (precision about 0.2mm) were later used to verify the results of the continuous tracking of the other two total stations. The MS50 went back to scanning mode after completion of the single point measurements.

Fibre Optic Monitoring Concept

For the early detection of a possible dam failure and investigations on creeping effects high frequent measurements with a precision of better than 1/100mm were necessary. For this purpose, we installed a fibre optic monitoring system based on fibre bragg gratings (FBG) on the dam surface. Using FBG sensors the distance changes between the anchor points P1 and P2 (FBG1) and between P2 and the reference point P3 (FBG2) were measured, see Figure 5.

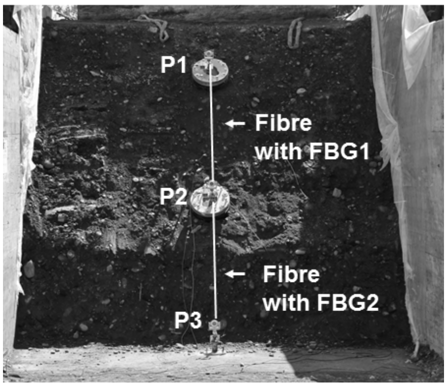


Figure 5. Fibre optic measurement setup

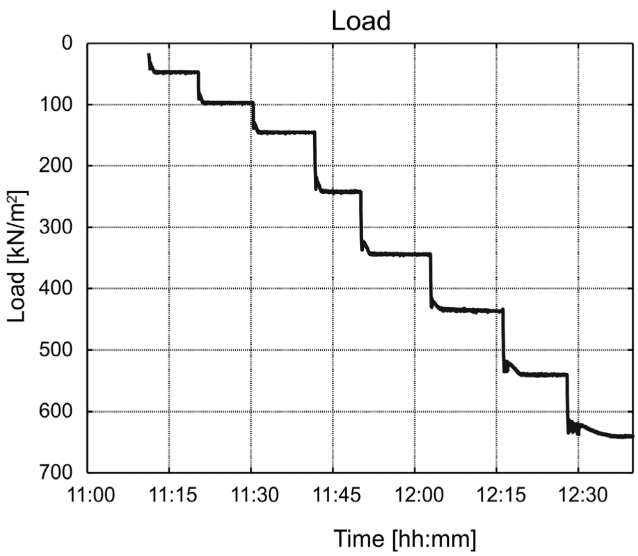
In the given experimental setup only shortening of the gage length of the sensors occurs. However, as the position of the Spideranchors after installation could deviate by about 5 to 10cm from their initial position FBG sensors with an adjustable length had to be used. Thus, cylindrical adapters (Figure 4-right) for adjusting the fibre length of bare fibres were developed.

FBG sensors are sensitive to strain and temperature changes, see e.g. Othonos und Kalli (1999, pp. 98). The raw wavelength measurements have to be converted into either strain or temperature values by appropriate conversion functions. For the FBG sensors used no appropriate strain and temperature sensitivity values were available from the manufacturer. Therefore, these coefficients had to be determined by laboratory investigations. Details about the derived temperature and strain calibration functions can be found in Lienhart *et al.* (2013). Due to the expected large deformations of several centimetres and the short distances of about 1.3m between the anchor points the measurement concept had to be prepared for high strain values. As a consequence draw tower gratings (DTG, FBGS International) were used. For different reasons temperature compensation of the FBG measurements was performed using electrical temperature measurements (thermocouples) in the vicinity of the FBG sensors in the dam experiments.

MONITORING RESULTS

Absolute Anchor Head Movements

In this article we concentrate on the results of one individual experiment (30.08.2012). In this experiment Spideranchors were used as a stabilisation method. The load was gradually increased up to 650kN/m^2, Figure 6-left, and caused movements of the anchor heads. The tracking data of the two total stations is shown as grey dots in Figure 6-right. P1 and P2 experience different deformation behaviour. The movements of P1 are predominately horizontal whereas P2 moves almost the same amounts horizontally and vertically. The total movements are about 4.8mm for P1 and 3.2mm for P2 and show a high stability of the Spideranchors.



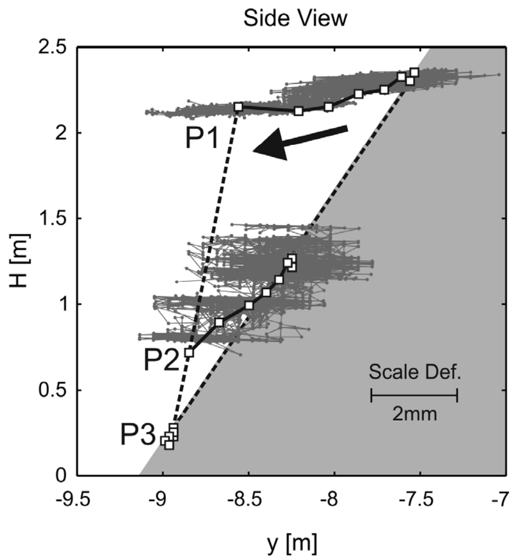


Figure 6. Applied load (left), movements of anchor heads (right)

The noise of the tracking data is mainly caused by the noise of the distance measurements of the total stations. For the 3D position a precision of 0.9mm (1 σ) could be achieved. As previously mentioned single point measurements were made with the MS50 to verify the continuous tracking data of the other two total stations. The single point measurements are shown as white squares in Figure 6-right. As expected the tracking data follow these points which confirms the stability of the two tracking total stations. The 3D point precision of the MS50 measurement can be calculated from the measurements to the surrounding control network. The determined 3D point precision of 0.2mm (1 σ) is about 4 times better than the precision of the tracking data.

Relative Anchor Head Movements

Relative anchor head movements can be calculated from the geodetic 3D positions or directly be measured with the fibre optic sensors. Figure 7 shows the results of the dynamic fibre optic measurements. It can be seen that the FBG sensors depict relative movements between the anchor points immediately after the load is increased. Furthermore, the creeping behaviour of the movements, e.g. between 12:18 and 12:25, is visible by these measurements.

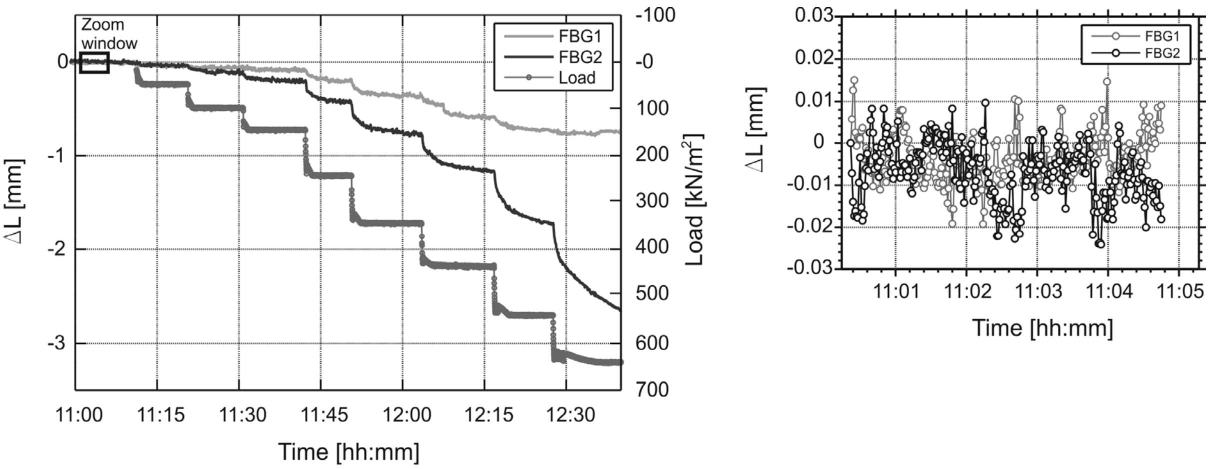


Figure 7. Results of dynamic fibre optic measurements compared to the load steps (left) and a zoom of the FBG measurements during the initial stable phase showing the measurement noise (right)

The distance between the anchor heads P1 and P2 (FBG1) and the distance between P2 and the fixed reference point P3 (FBG2) was decreasing as expected. The length change at the end of the experiment is about 0.8mm (approx. 600με) for the distance P1-P2 and about 2.7mm for the distance P2-P3 (approx. 2200με).
The measurement noise of the FBGs was evaluated by analysing the data of the initial stable period. Figure 7-right shows the measurement variations within 5 minutes in the unloaded state of the experiment. A standard deviation of better than 7μm can be derived from these data for both sensors which is remarkable keeping in mind the difficult measurement conditions in the field.

To verify the results, we compared the FBG measurements with the TS15 total station measurements. Figure 8 shows the results of the two different measurement techniques. Displayed are the distance changes between the anchor point P1 and the fixed reference point P3. This corresponds to the sum of the two FBG readings. For the geodetic data distances were calculated from the continuously tracked 3D coordinates of P1 and the known coordinates of the fixed reference point P3. Although the precision of the geodetic and fibre optic measurement techniques is completely different, it can be seen that the overall deformation can also be detected with the dynamic and static geodetic measurements. However, the deformations caused by the individual loading steps and the creeping behaviour are only measurable with the fibre optic sensors.

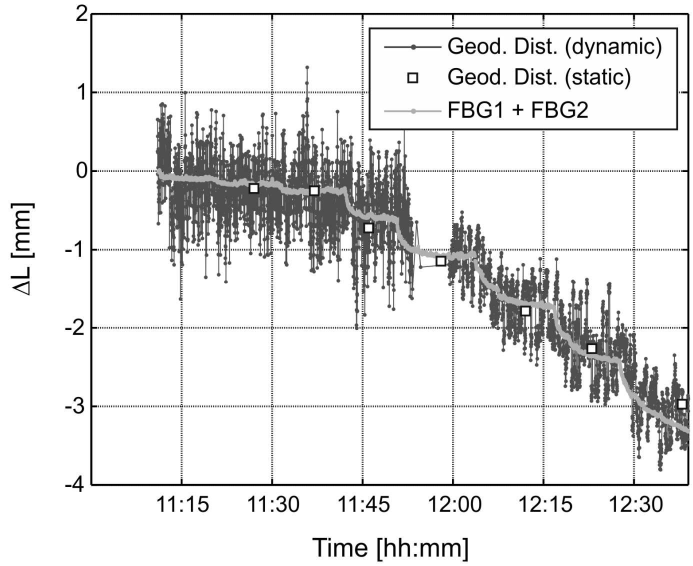


Figure 8. Length changes between P1 and P3 derived from geodetic and fibre optic measurements

Surface Movements

The whole dam surface was scanned initially and at the end of each loading step with the Leica MS50. The time for completing one scan was about 2min when using a distance measurement update rate of 1000Hz. Figure 9-left displays the measured point cloud of one of these surface scans. The point cloud shows details of the dam surface and the experimental setup. In a first step we focus on the analysis of individual measurement profiles. Figure 9-right indicates one horizontal (HP1) and one vertical profile (VP1) which are used for a detailed analysis of the dam deformations. The range noise of the instrument in scanning mode is specified as 1.0mm (Leica Geosystems 2013) for measurements with 1000Hz orthogonally to a target plane with 90% reflectivity. Field measurements typically result in a lower precision due to inclined measurements to natural targets with rough surfaces and lower reflectivity. In case of the dam experiments measurements with low incidence angles could be avoided on the dam surface due to a high instrument setup on a small hill about 2.5m above the foundation plate and the steep slope.

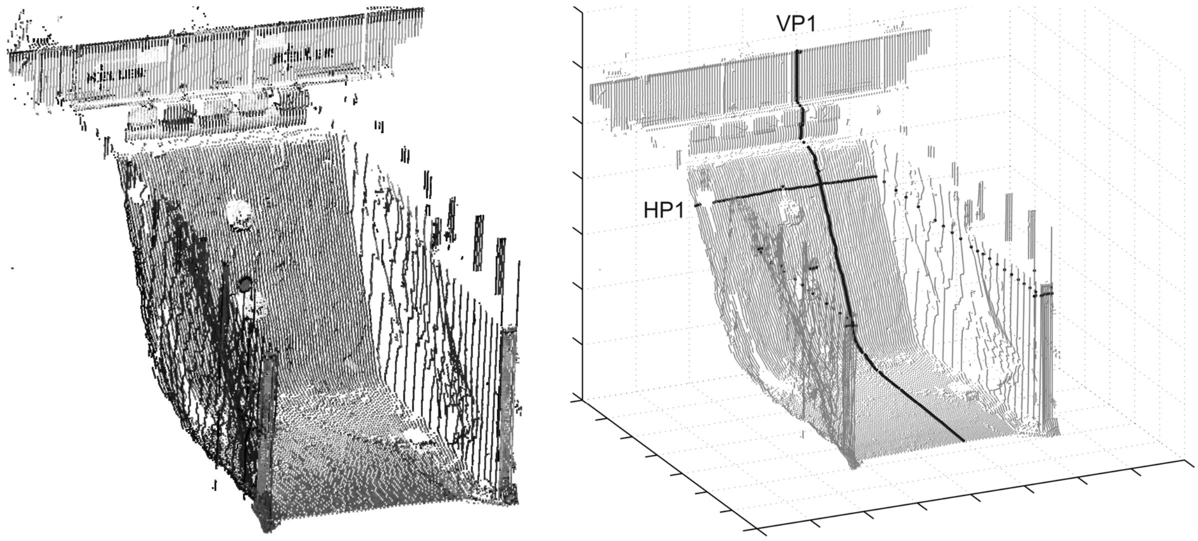


Figure 9. Point cloud of dam surface (left), profiles (black lines) for detailed analysis (right)

The differences of the vertical scan line before loading and after the last loading step are shown in Figure 10-left. The deformations are exaggerated by a factor of 5 for better visibility. It can be seen that deformations of several centimetres occurred, especially in the upper part (above the height of the Spideranchor SP1) which bulges out. The lower part of the slope is almost stable, which was also the result of the anchor head measurements described before. In some areas material slides down the slope and accumulates at the toe of the slope.

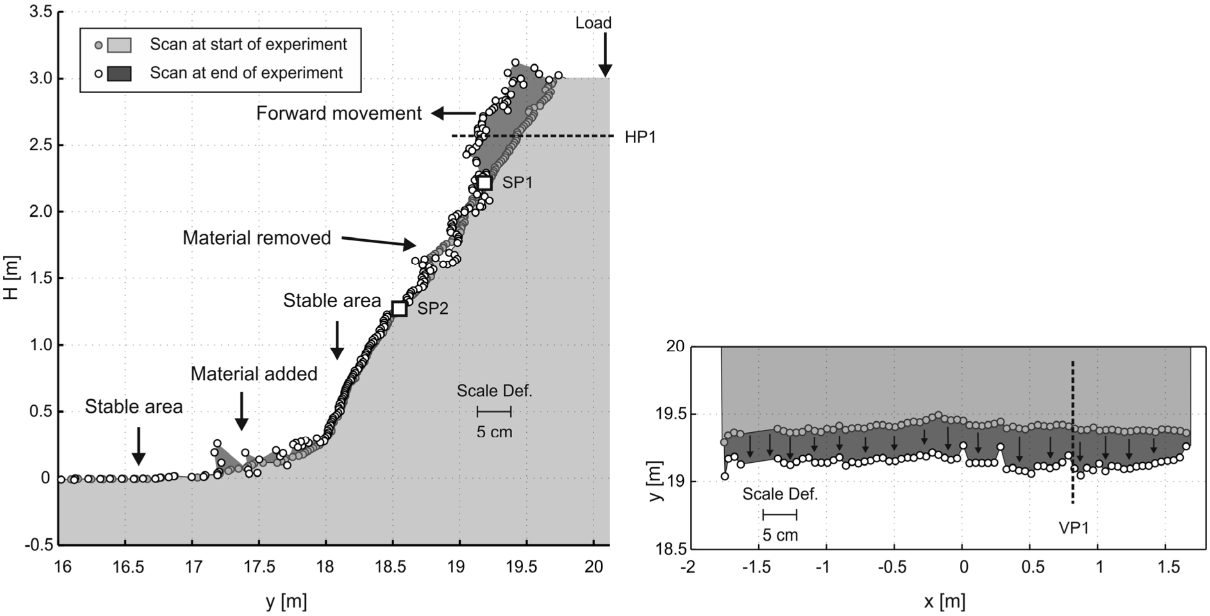


Figure 10. Deformations along the vertical scan line VP1 (left) and the horizontal scan line HP1 (right) between the start and the end of the experiment

Figure 10-right displays the deformations along the horizontal cross section HP1. It can be seen that the slope material moves several centimetres forward along the whole cross section.

Finally, deformations were derived from the whole point cloud. The deformation analysis was performed with the software Geomos v6.0 from Leica Geosystems.

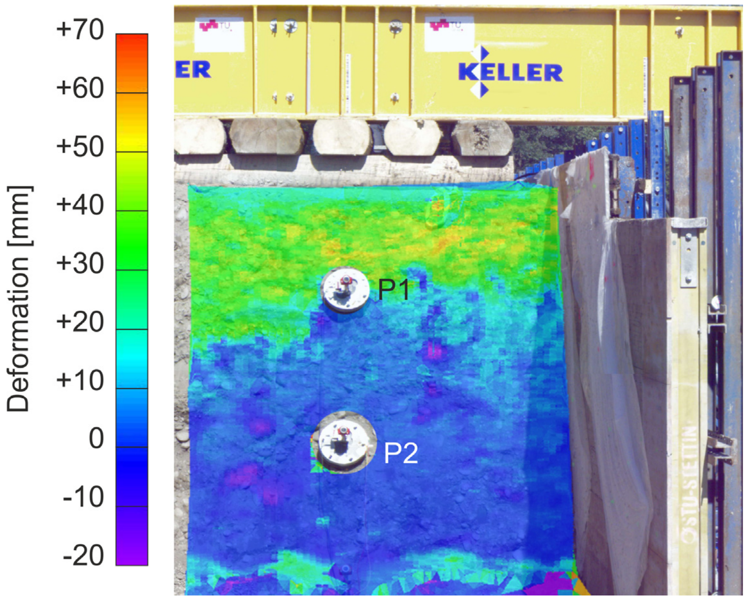


Figure 11. Deformations calculated form the point clouds of the start and the end of the experiment

Figure 11 displays the calculated surface deformations. As could already be seen in the cross section analysis, the upper part of the slope experiences a forward movement of several centimetres. These movements are more than ten times higher than the movements of the anchor heads. The area below the anchor P1 is either stable or experiences only small deformations in the range of a few millimetres. Negative deformation occurred only in a few areas where material was sliding down. This material, mostly stones, accumulated at the toe of slope, see Figure 11.

CONCLUSIONS

In this paper we reported on the deformation monitoring of an earth filled dam. We demonstrated in our evaluation that absolute 3D deformations can be reliably derived from geodetic point measurements. In our experiment a 3D point precision of about 0.9mm (1 σ) in case of dynamic measurements and 0.2mm (1 σ) in case of static measurements could be achieved. The absolute anchor head movements were even in high load situations very small and below 5mm.

The MS50 MultiStation could easily be integrated into the monitoring system. The analysis of the collected point clouds proved further the high performance of the stabilization methods. Large movements of several centimetres of the slope surface occurred only above the Spideranchors.

However, individual loading steps cannot be resolved due to the limited precision of the geodetic measurements. Our results demonstrate that the sensitivity of the monitoring system could be increased significantly with the fibre optic sensors. A precision of better than 7µm was achieved in the field experiments. This high precision allows an analysis of the deformation behaviour of each loading step including the creeping behaviour of the slope.

The used setup enables a direct comparison between the geodetic and fibre optic measurements. The gage length can be easily adjusted through the use of bare fibres. However, handling the bare fibres on a construction site is a challenging task and requires special attention. The developed measurement concept is not limited to earth structures. The mounting adapters can also be applied on other civil engineering structures for temporary monitoring tasks.

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